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Life cycle assessment of a two-seater all-electric aircraft

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Abstract

Purpose Aviation is an important contributor to climate change and other environmental problems. Electrification is one option for reducing the environmental impacts of aviation. The aim of this study is to provide the first life cycle assessment (LCA) results representing an existing commercial, two-seater, all-electric aircraft.

Methods An attributional cradle-to-grave LCA was conducted with a functional unit of 1 h flight time. Data and records from an aircraft manufacturer informed much of the study. Detailed modelling of important aircraft components is provided, including the battery, motor, inverter, instrument panel and seats. Impact results are compared to those from a similar but fossil fuel–based two-seater aircraft. A wide range of impact categories was considered, while the focus was on global warming, resource depletion, particulate matter, acidification and ozone formation.

Results and discussion The main contributors to almost all impact categories are the airframe, the lithium-ion battery and emissions (in the use phase). The airframe has a major impact as it contains energy-intensive, carbon fibre–reinforced composites, the impact of which can be reduced by recycling. The battery dominates mineral resource depletion categories and contributes notably to emission-based categories. Producing batteries using non-fossil energy or shifting to less resource-intensive, next-generation batteries would reduce their impact. Use-phase impacts can be reduced by sourcing non-fossil electricity. Despite the need for multiple battery pack replacements, the comparison with the fossil fuel option (based on equal lifetimes) still showed the electric aircraft contributing less to global warming, even in a high-carbon electricity scenario. By contrast, when it concerned mineral resources, the electric aircraft had greater impact than the fossil fuel based one.

Conclusions A sufficiently long lifetime is key to bringing the all-electric aircraft's environmental impacts (such as global warming) below those of fossil fuel–based aircraft. The high burden of the airframe and batteries can then be outweighed by the benefit of more efficient and emission-free electric propulsion. However, this comes with a trade-off in terms of increased mineral resource use.

Keywords Climate change · Aircraft · LCA · Electromobility · Lithium-ion battery

1 Introduction

Aviation has grown considerably in recent decades and accounts for approximately 2% of global carbon dioxide (CO_2) emissions and some 4% of all climate change impacts annually (Lee et al. 2021). Contributions to climate impacts from aviation include (in addition to CO_2 emissions) contrail cirrus cloud formation, nitrogen oxide emissions and water vapour emissions. Long-haul flights can drastically increase the carbon footprint of individuals. For example, a single round-trip flight from Berlin to Bangkok releases about 3 metric tonnes of CO_2 per person, which is more than the average of 2 tonnes per person required to meet global climate targets for 2050 (Girod et al. 2014). In response to the high climate change impacts of fossil fuel–based aviation, technological alternatives (presumably with lower environmental impacts) have been proposed. The two main options are (i) reducing the energy requirement of flying by, e.g. reshaping aircraft bodies (airframe), and (ii) reducing the emission intensity by such things as replacing the current kerosene fuel with bio-based kerosene, liquid hydrogen

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or fuel-cell systems in jet engines or by using electricity stored in batteries (Hepperle 2012; Dahal et al. 2021; Lai et al. 2022). Aircraft propelled by electricity from a battery may be either all-electric or hybrid electric, depending on whether other propulsion options are also used (Brelje and Martins 2019). This study concerns the environmental impacts of an all-electric aircraft. All-electric aircraft eliminate all direct climate change contributions during flight (such as CO_2 emissions and contrail formation) and reduce local air pollution and noise (Sahoo et al. 2020). However, producing aircraft components, assembling aircraft and making electricity for charging them still cause environmental impacts.

As pointed out by Hepperle (2012), electric aviation is not entirely new; as early as 1973, a nickel–cadmium battery was able to power a 15-min flight in a small demonstration aircraft. Today, electric road vehicles and other battery-powered applications rely instead on lithium-ion batteries (LIBs). As-yet uncommercialised battery chemistries, such as lithium-sulphur and lithium-air, might provide even better performance for aviation in such areas as energy storage per mass of battery (specific energy) (Sahoo et al. 2020). In its roadmap for aircraft technology development up to 2050, the International Air Transport Association (2019) refers to all-electric aircraft as a “revolutionary” technology and envisages larger all-electric aircraft (50–80 seats) by around 2035–2045, following a preceding penetration of smaller, all-electric and hybrid electric aircraft between 2020 and 2040. Over 70 different all-electric aircraft have been researched since the late 2000s, either conceptually, experimentally or commercially (Gnadt et al. 2019). However, as they are limited by the performance of current LIBs and other factors, today’s all-electric aircraft are restricted to smaller one- or two-seater aircraft (Hepperle 2012; Brelje and Martins 2019; Gnadt et al. 2019).

The International Civil Aviation Organization (2019) writes in a report that “[a] life cycle approach to electric aircraft could be useful to assess the overall impact of electric aircraft on the environment and its sustainability benefits”. Similarly, Hepperle (2012) writes that an important question to address regarding electric aviation is “how does the total energy balance and the environmental footprint including manufacturing look like?” The present study begins to address this question. The specific aim is to provide the first LCA results representative of an existing commercial two-seater all-electric aircraft. To put the results into perspective, they will be compared with those from a similar but fossil fuel–based two-seater aircraft.

To the best of our knowledge, this is the first LCA study of a current all-electric aircraft—all previous LCAs on all-electric aircraft have considered hypothetical future aircraft. Ploetner et al. (2016) considered an all-electric aircraft concept called the Ce-Liner, potentially entering into service around 2035 for journeys longer than 1000 km with 189 passengers. The results showed that the hypothetical Ce-Liner had only minor climate change impacts compared to fossil fuel–based aircraft, given low CO_2 electricity mixes based on renewables or nuclear power. Similarly, Schäfer et al. (2019) assessed the climate change impacts of a hypothetical future all-electric 150-passenger aircraft concept flying about 740 km using different electricity mixes (Brazil, the EU, the USA, China and globally), assuming a future battery capacity of 800 Wh/kg. They found that the CO_2 intensity of the Chinese mix (approx. 650 g CO_2/kWh) was sufficient to break even with current fossil fuel-based aircraft, provided that the non-CO_2-related climate change effects of fossil fuel–based aircraft were also considered. Gnadt et al. (2019) assessed the CO_2 emissions of a hypothetical 180-passenger, all-electric aircraft concept with a 370–3000-km range, assuming a future improved battery capacity of 400–2000 Wh/kg at pack level. The lower range was reportedly achievable through improvements in LIBs, while the higher capacities would require new types of batteries. The assessment concluded that (assuming a transition towards more renewable electricity) CO_2 emissions lower than those of fossil fuel–based aircraft were achievable. While such assessments of hypothetical large aircraft concepts are interesting for outlining the future potential of this emerging technology, it is also relevant to complement these studies with assessments of the technology in its current state. Furthermore, the studies by Schäfer et al. (2019) and Gnadt et al. (2019) only assessed the impacts of producing the use-phase electricity and battery. This study includes the whole aircraft, its use phase and waste treatment.

2 Methods and materials

The studied aircraft was modelled based on the Alpha Electro, a two-seater all-electric aircraft produced by Pipistrel, a company in Slovenia and one of a few commercially available all-electric aircraft (Brelje and Martins 2019). However, due to incomplete data and an aim to provide more generic results, the modelled aircraft is not identical to the Alpha Electro. Unless otherwise indicated, the data used stems from open-access documentation about Alpha Electro online or has been kindly provided by Pipistrel. Important online documents include the Alpha Electro aircraft information report (2017) and a Dutch Safety Board (2020) report. The composition of the two-seater all-electric aircraft can be found in Table 1. The modelled aircraft accounts for 96% of the mass of an Alpha Electro with an empty weight of 370 kg. This was deemed to provide sufficient detail and data coverage to represent a generic, two-seater, all-electric aircraft.

Table 1 Two-seater electric aircraft composition

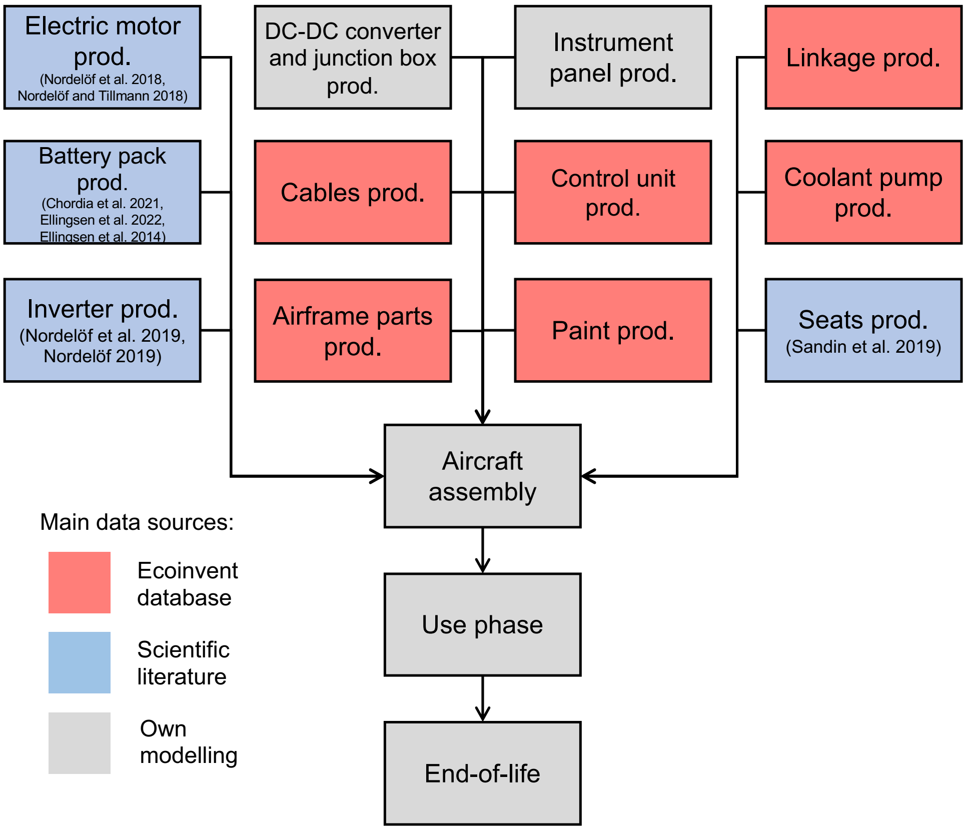
Component	Mass (kg)	Description
Electric motor	20.5	Permanent magnet motor, 60 kW
Battery packs	116	Two lithium-ion battery packs, cylindrical NMC cells, 21 kWh
Battery management system (BMS)	2.0	Electronic component
12-V battery	1.4	Lithium-ion battery
Inverter	7.0	Power electronic component
Cables	7.0	AC and DC cables, 400 V
DC-DC converter	0.30	Power electronic component
Junction box	0.65	Electrical component
Airframe parts, total	173	Carbon fibre composite
Fuselage (incl. fin)	58	Carbon fibre composite
Wings	74	Carbon fibre composite
Propeller	3.5	Carbon fibre composite
Horizontal tailplane	6.0	Carbon fibre composite
Legs	6.0	Glass fibre composite
Flaperons	10	Carbon fibre composite
Elevator	1.8	Carbon fibre composite
Other composite parts	2.7	Carbon fibre composite
Tyres	4.0	Rubber
Wheels	3.0	Aluminium
Doors	2.5	Polycarbonate and carbon fibre composite
Windows	1.8	Polycarbonate
Exterior paint	2.0	Polyurethane paint
Two coolant pumps	1.3	Steel and polypropylene
Control unit	1.2	Electronic component
Two seats	3.8	Glass fibre composite, foam, cotton, rubber
Linkage	12	Aluminium alloy
Instrument panel	7.0	Electronic components, copper, composite, plastics
Total mass	**355**	-

Different functional units can be applied in environmental assessments of modes of transport (Roth and Kåberger 2002). Since the function of a small two-seater aircraft like the Pipistrel Alpha Electro is for pilot training or leisure flights, the functional unit of the study is 1 h of flying (flight hour). For larger aircraft whose function is the efficient transport of freight or people between locations, distance-related functional units (vehicle-, person- or ton-km) are more relevant; but this is not the function of this two-seater electric aircraft. Since the aim of the study is to provide initial life cycle impact results for an all-electric aircraft, enabling hotspot analysis and comparisons to fossil fuel–based counterparts, an attributional LCA has been conducted. In this, environmentally relevant physical flows to and from a product and its life cycle are quantified (Finnveden et al. 2009). Allocation by cutoff was applied to recycled materials throughout the system, meaning that the inclusion of such materials only accounts for their direct impact during recycling processes and not further upstream (Ekvall and Tillman 1997). This means that recycled materials are "cut off", or not followed anymore, while a share of recycled materials can be introduced upstream, reducing the impact of material production (Nordelöf et al. 2019b). Data from the Ecoinvent database version 3.8 was used (Wernet et al. 2016) for most background processes, like electricity and material production. Unless otherwise stated, global datasets were applied or, if unavailable, average data for Europe or the rest of the world. Figure 1 provides an overview of the life cycle of the studied aircraft and data sources that were used; these are further described in the following sections.

2.1 Electric motor production

The modelling of the electric motor is based on a manual for Emrax motors, which provides technical specifications and drawings for a series of axial flux permanent-magnet synchronous machines of similar design (Emrax 2020). The motor used in the Alpha Electro is the Emrax 268 version, which gives the aircraft a rated motor power of 60 kW (Dutch Safety Board 2020). This motor weighs 20.5 kg, with about 40% of this mass assigned to rotating parts (Emrax 2020). Information from the Emrax manual, photographs from a disassembly study of the smaller Emrax 228 (BuildIts in Progress 2017), geometrical analyses and a comparison of

Fig. 1 Flowchart providing an overview of the life cycle of the two-seater all-electric aircraft studied, with main data sources shown



the two designs enabled a subcomponent and material specification to be estimated for the Emrax 268. This approach also provided the surface area of the aluminium housing motor parts, which could be assumed to undergo anodisation as a surface treatment. In a subsequent step, the composition data was coupled to motor production data available in the scalable life cycle inventory model reported in Nordelöf et al. (2018) and Nordelöf and Tillman (2018), to establish full motor and magnet supply chain inventory data. Also included from the same sources was a typical motor measurement device, called a resolver, weighing about 70 g. Data for the anodisation process per surface area was obtained from Nordelöf (2019). Table S1 shows the unit process data for the entire electric motor production.

2.2 Battery pack production

The Alpha Electro contains a 21-kWh nickel-manganese-cobalt (NMC) type lithium-ion, high-voltage battery, arranged in two packs with cylindrical cells. The combined mass of these two packs is 116 kg, with an additional 2 kg of battery management system (BMS). In this study, the cells were modelled as NMC811 21,700 cylindrical cells (based on Chordia et al. 2021). A total of 1400 cells, together weighing 94.5 kg, was required to achieve the specified storage capacity. The remaining 21.5 kg of the two packs was assigned to module and pack parts, assuming four modules per pack and one external high-voltage connector per pack. The composition of module and pack parts was obtained from Winjobi et al. (2020) and combined with our engineering estimates of the manufacturing processes required to make them. Data for these manufacturing processes was obtained from Ecoinvent datasets, such as metalworking and injection moulding. The two high-voltage connectors were estimated to contain a total of 295 g of copper and 11 g of plastics, by comparing the mass of two almost identical Amphenol connectors, differing only in terms of housing materials (Farnell 2022; Mouser Electronics 2022). Since the battery cells in the Alpha Electro are provided by a South Korean battery producer, it was assumed they were produced using South Korean electricity and heat.

Data for the electronic and electrical equipment of the BMS was acquired mainly from Ellingsen et al. (2022), under an assumed fixed-size logic control board and number of low-voltage systems parts per module. However, the logic control boards for the packs were downscaled based on storage capacity. Data on the high-voltage system parts for the remaining specified mass of the BMS (and the assembly energy) was obtained from Ellingsen et al. (2014).

The much smaller 12-V battery weighs 1.4 kg and is also reported to be of lithium-ion type. For simplicity, it has been proxied as a small version of the high-voltage battery packs, effectively corresponding to an upscaling of the total modelled battery mass from 116 to 117.4 kg. Table S2 shows the unit process data for the entire LIB pack production.

2.3 Power electronic and electrical components production

In addition to the motor and battery, the electric powertrain also contains a power electronic motor controller (an inverter), which converts the battery's DC to AC to run the motor. In turn, this component contains several electronic and electrical subparts: a power module with transistor switches, a large capacitor, copper busbars, high-voltage connectors, a signal connector, an electronic driver board, an electronic logic board, various interconnects and combined casing and liquid-cooled heatsink. For the Alpha Electro, the specified inverter mass is 7 kg. An existing inventory data model for an inverter was used to model this part, as described in Nordelöf et al. (2019a) and Nordelöf (2019). All internal parts of the unit were set to match the 60-kW requirement for the rated power supply to the motor, giving a total mass of about 3.5 kg. The remaining mass was assigned to the casing and liquid-cooled heatsink made of aluminium, with an estimated surface area of 29.6 dm^2 for anodisation. Table S8 shows the unit process data for the inverter production.

To charge the low-voltage battery and power all regular electronic devices, the high-voltage battery is connected to a DC-DC converter. In the Alpha Electro, this is a slimmed-down electronic component of 0.3 kg, the functions of which are contained on a printed circuit board. A somewhat larger converter for an automotive application, converting 400 V to 12 V at relatively high power, was found in descriptions from Texas Instruments (2021), but without any mass or subcomponent specifications. Instead, an engineering report for a demo board of a switched-mode power supply for general electronics use was used as a source of board measurements and a component list. This served as a proxy in the same mass range and better matched a 350-W power rating than the automotive option (Infineon 2018). The mass of the unmounted board panel, solder and coating was estimated based on the stated board size. All components were counted and checked for their reported mass with online component suppliers; they were also matched with available datasets for electronic board components in the Ecoinvent database. The remaining mass was assigned to a plastic structure required for mounting the converter into an aluminium junction box. Table S9 shows the unit process data for the DC-DC converter production.

The total mass of the junction box was specified at 0.95 kg, including the DC-DC converter, leaving room for about 300 g of relays, 100 g of cables and 50 g of rubber grommets, all in a thin-walled box with multiple openings for cable leads, constructed from 200 g of aluminium. These materials were combined with matching manufacturing datasets in the Ecoinvent database. Data for the composition of the relays was established by comparing environmental product declarations for three different contactors, which is the type of relay specified (ABB 2007; Schneider Electric 2013; Legrand 2019). One of the identified constituents is iron, which is typically pure industrial iron, such as electrolytic iron. Data for the energy required to press and sinter this part (and manufacture electrolytic iron) was compiled from Nordelöf and Alatalo (2018). Table S12 shows the unit process data for producing the junction box (excluding the adjacent DC-DC converter).

The production of high-voltage cables connecting powertrain components was modelled using the generic dataset "market for cables, unspecified" in the Ecoinvent database.

2.4 Production of other components

About 92% of the airframe parts consist of carbon fibre composites. There are also glass fibre composites in the legs, as well as polycarbonate in the doors and windows. These materials were modelled using their respective market processes in the Ecoinvent database. Also modelled was a market process of injection moulding; this accounts for the flows (energy and material losses) involved in forming materials into components. The rubber in the tyres was modelled using the Ecoinvent market process for synthetic rubber. The aluminium in the wheels was modelled using the market process for primary aluminium ingot, plus a market process for lost-wax casting to account for manufacture of the wheels. See Table S13 for unit process data for the airframe parts.

The instrument panel consists of carbon fibre composites, copper, polyethylene terephthalate, ethylene tetrafluoroethylene (trade name Tefzel), plus displays and electronics. The carbon fibre composite was modelled using an Ecoinvent market process dataset that also includes injection moulding. The copper was modelled using the market process for cathode copper and a market process for metalworking of copper products. The polyethylene terephthalate was modelled using an Ecoinvent market process, while the ethylene tetrafluoroethylene production data was obtained from a report by Jungbluth et al. (2012). In both cases, a market process for injection moulding was applied to account for the shaping of the material. The displays and electronics in the instrument panel were modelled as "mobile phone equivalents". That is, in terms of displays and electronics, they were assumed to have a mass proportional to that of a standard mobile phone. In addition to its display and electronics, a mobile phone generally consists of a battery and a housing (Tan 2005). However, in the case of an electric aircraft instrument panel, these parts are covered by the aircraft's 12-V battery as well as the instrument panel's composite and plastic parts. While several LCAs of mobile phones have been conducted (Tan 2005; Ercan 2013; Andrae and Vaija 2014; Corcoran et al. 2014; Ercan et al. 2016; Prosle et al. 2016), the most transparent and user-friendly LCI data was found in the study of a Fairphone by Güvendik (2014) and was thus used in this study. Table S14 shows the unit process data for the entire instrument panel production.

The powertrain control unit was modelled based on the Ecoinvent process "electronics production, for control units", with two modifications. First, the casing is changed from steel to an equal volume of aluminium to better match the weight requirements of aircraft components. Second, the electronics are changed to modern, lead-free electronics. Because of the high density of steel and lead, these substitutions lead to a change in the mass configuration of the control unit, equivalent to the reference flow of 1 kg in the original unit process being reduced to 0.68 kg. These revised mass proportions were then scaled to 1.2 kg, which is the mass of the control unit in the two-seater electric aircraft.

The paint used is a polyurethane water-based paint, for which the production was modelled using a market process for polyurethane adhesive in Ecoinvent. The aluminium alloy linkages are made from the so-called 6000 series, which alongside approx. 98% aluminium also contains approx. 1% silicon, approx. 1% magnesium and possibly some additional metal(s). The closest dataset in the Ecoinvent database is "market for aluminium alloy, AlMg3". However, this dataset contains 3% magnesium and no silicon, which means that the magnesium content is slightly overestimated and the silicon content neglected. The market process for metalworking of aluminium products was included to account for manufacturing the linkages.

The two small (0.66 kg each) coolant pumps are identical and consist of steel (70%) and polypropylene (30%). Their production was modelled based on these inputs and shaped by casting and injection moulding, respectively. The unit process for pump production is shown in Table S15.

The seats consist of glass fibre–reinforced plastic, foam, cotton and a smaller amount of rubber. The production of the seats was modelled based on these constituent materials. The non-cotton materials were all modelled using market processes in Ecoinvent, with the foam assumed to be polyurethane. The cotton upholstery was modelled as denim, a strong cotton fabric that undergoes process steps the upholstery is also likely to undergo. The production of cotton yarn was modelled using a market process for yarn in Ecoinvent. The continued production of denim from yarn was modelled based on the jeans production described in Sandin et al. (2019) (but without the elastane additive), including the datasets for bleaching, dying and drying cotton yarn, as well as weaving and confectioning. See Table S16 for the seat production unit process dataset and Figure S1 for an illustration of the cotton upholstery production modelling.

2.5 Aircraft assembly

All components in Table 1 are put together in the electric aircraft assembly step. For this, approximately 900 kWh/aircraft is required at Pipistrel's factory in Slovenia. That value is based on the top-down electricity requirement of the entire factory and thus includes all the factory's operations. Although other aircraft besides the Alpha Electro are produced there, they all belong to a similar size class, which is why the same electricity requirement per aircraft produced has been assumed. Two scenarios for sourcing electricity were considered—the average EU mix and a "green" choice modelled as the Norwegian electricity mix (approx. 90% hydropower), both based on Ecoinvent market processes. No data on emissions or waste generation from the aircraft assembly could be obtained, but these were estimated as being minor and therefore set at zero. However, one eligible operation within the factory is spray-painting, which likely emits volatile organic compounds (VOC) during spraying and drying. Nordelöf et al. (2017) used an emission factor of 92% of the dry paint mass which, in this case, gives 1.8 kg VOC/aircraft. The unit process for the electric aircraft assembly process can be found in Table S17.

2.6 Use phase

As this aircraft type is relatively new, data is not yet available for the average operation lifetime. Some Alpha Electros have been running for at least 500 flight hours (Waterloo Institute for Sustainable Aeronautics 2021), which is taken as a minimum lifetime scenario. This effectively corresponds to a scenario in which the entire aircraft is discarded when the battery packs installed in it during assembly start depleting. However, the corresponding fossil fuel aircraft, the Alpha Trainer (which shares most of the components and parts with the Alpha Electro) has been confirmed to run for at least 4000 flight hours (Pipistrel n.d.), indicating that most other parts of the Alpha Electro have much longer lifetimes than the battery packs. We assume this to be a high lifetime scenario for the electric aircraft. This means that a factor of 1/500 aircraft and 1/4000 aircraft are required per flight hour in the two scenarios, respectively. However, the electric aircraft's battery packs need to be replaced after 700 charging cycles (Pipistrel 2017) which, given a flight time of approx. 1 h per charge, translates to approximately 700 flight hours. This means that the short lifetime requires only one set of battery packs, whereas the high lifetime scenario requires six sets of battery packs in total; an initial one plus five replacements.

Regarding the charging electricity, the total storage capacity of the battery packs is 21 kWh, which can be used for a 45-min cruise, an additional 15 min for the other flight steps (standing, taxi, takeoff, climb, descent and landing) and a reserve of 20 min. This means that 60 out of 80 min in total are used every flight, or 75% of the total capacity. Thus, the average electricity use for each flight is $21 \times 0.75 = 16$ kWh/h. This value was verified as approximately reasonable by scaling the power demand cycle for a larger electric aircraft calculated by Hess et al. (2019) to the Alpha Electro based on its maximum power and assuming reasonable durations of the flight steps. A charging efficiency of 95% was furthermore assumed, meaning 5% electricity losses (ADB 2018). Again, two scenarios for sourcing charging electricity were considered—the average EU mix and a "green" choice modelled as the Norwegian electricity mix. The unit process for the use phase of the electric aircraft can be found in Table S18.

2.7 End of life

Since the cutoff approach to recycled materials is applied, only dismantling of the aircraft and separation into different waste and recycled fractions are included in the end-of-life modelling of recyclable materials, whereas all non-recyclable materials also undergo full waste treatment. Thus, recyclable materials are assumed to leave the product system studied to become secondary raw materials for other products, in the same way as several raw materials for producing aircraft components contained some recycled content, which entered burden-free upstream in the product system. All components are assumed to undergo initial collection, shredding, separation and sorting. This process might look slightly different for different components. For example, separation of the battery packs might involve manual disassembly and separate mechanical separation of different battery components depending on the intended subsequent recycling process (Xiao et al. 2020). Still, the same data for collection, shredding, separation and sorting was applied to all components. This represents a modern waste-handling facility, as reported by Tillman et al. (2020). For the battery pack, motor, cables, wheels, steel in coolant pump, linkages, copper part of the instrument panel, plus all electronic components (BMS, inverter, DC-DC converter, junction box, control unit and the "mobile phone equivalents" of the instrument panel), this first process is assumed to result in recyclable materials that are cut off. All carbon fibre composites, glass fibre composites, polycarbonate, polypropylene in coolant pumps, polyurethane foam in seats, polyethylene terephthalate, ethylene tetrafluoroethylene and exterior paint are assumed to become waste plastic, which is further treated using the European market process for waste plastic in Ecoinvent. This process contains varying shares of landfill and incineration as per the EU member states' current waste handling of plastic. The rubber from the tyres and seats is similarly assumed to be further treated using the European market process for waste rubber, and the cotton from the seats is assumed to be further treated using the European market process for soiled waste textiles.

The batteries are assumed to be removed manually before the shredding, after which they are considered recyclable and can undergo pyrometallurgical or hydrometallurgical treatment (Harper et al. 2019).

Table 2 shows the respective end-of-life processes for each aircraft component. The unit process for the end of life of the electric aircraft can be found in Table S19.

2.8 Fossil fuel-based aircraft

Just as the model Alpha Electro was used as a template for the electric two-seater aircraft, its sister model, the Alpha Trainer, is used as a template for the fossil fuel–based two-seater aircraft. The two aircraft are very similar except for the powertrain; the fossil fuel–based aircraft has no electric motor, battery, inverter, DC-DC converter, high-voltage cables or junction box. Instead, it has a combustion engine with a fuel pump and fuel tank. The remaining components were assumed to be identical to those of the Alpha Electro. The combustion engine weighs 55 kg and some related components weigh about 13 kg (Rotax 2021). This gives 271 kg in total, whereas the typical empty weight is 279 kg (Pipistrel 2013). This difference was assumed to be the fuel tank, which can hold 50 L fuel combusted at a rate of 9.5 L/h during flight (or 6.7 kg/h given a density of 0.7 kg/L). The engine was modelled using Ecoinvent's available dataset for a conventional internal combustion engine of a road vehicle. It also contains the following associated components, for which material compositions were assumed: exhaust system (4.0 kg, titanium), overload clutch (1.7 kg, low-alloy steel), engine suspension frame (2.0 kg, low-alloy steel), air guide baffle (0.8 kg, aluminium), airbox (1.3 kg, aluminium), fuel tank (calculated as 8.1 kg, carbon fibre composite), alternator (3.0 kg) and fuel pump (assumed to be 0.67 kg) (Rotax 2021). The alternator, which consists of multiple subparts of different materials, was based on composition data for a conventional generator from Schau et al. (2012), scaled to 3.0 kg (Rotax 2021) and further combined with likely processing steps found in Ecoinvent. The fuel pump was assumed to be equal to the two coolant pumps. The airframe, 12-V battery, paint, coolant pumps, control unit, seats, linkages, instrument panel and the assembly step were all modelled in the same way as for the electric aircraft, applying the EU mix for the energy requirement of the aircraft assembly.

The lifetime of the fossil fuel–based aircraft was assumed to be 4000 h, as confirmed for an Alpha Trainer used at a flight school in New Caledonia (Pipistrel n.d.). The fuel combusted during use is typically leaded aviation fuel (Hospodka et al. 2020), which is modelled here as regular petrol with an added quantity of lead to reach a typical concentration of 0.8 g/kg. Metallic lead was used here as proxy but, in reality,

Table 2 End-of-life processes for the two-seater electric aircraft components

Component	Treatment for separation	Waste treatment
Motor	Collection, shredding and sorting	Cutoff
Battery packs		Cutoff
BMS		Cutoff
12-V battery		Cutoff
Inverter		Cutoff
Cables		Cutoff
DC-DC converter		Cutoff
Junction box		Cutoff
Airframe parts		Waste plastic treatment
Fuselage (incl. fin)		Waste plastic treatment
Wings		Waste plastic treatment
Propeller		Waste plastic treatment
Horizontal tailplane		Waste plastic treatment
Legs		Waste plastic treatment
Flaperons		Waste plastic treatment
Elevator		Waste plastic treatment
Other composite parts		Waste rubber treatment
Tyres		Cutoff
Wheels		Waste plastic treatment
Doors		Waste plastic treatment
Windows		
Exterior paint		Waste plastic treatment
Two coolant pumps		Cutoff
Steel		Waste plastic treatment
Polypropylene		
Control unit		Cutoff
Two seats		Waste plastic treatment
Glass fibre composites		Waste plastic treatment
Foam		Waste rubber treatment
Rubber		Waste textile treatment
Cotton		
Linkage		Cutoff
Instrument panel		Waste plastic treatment
Carbon fibre composite		Cutoff
Copper		Waste plastic treatment
Ethylene tetrafluoroethylene		Waste plastic treatment
Polyethylene terephthalate		Cutoff
“Mobile phone equivalents”		

organometallic tetraethyllead is used. Approximated use-phase aviation fuel emissions during flight (including lead emissions) were obtained from Hospodka et al. (2020). Note that additional climate impacts from contrails and nitrogen oxide emissions at high altitudes (which can be significant for fossil fuel–based aviation (Azar and Johansson 2012)) are not expected to occur at the altitudes (< 5500 m) at which a two-seater aircraft flies (Pipistrel 2013).

Similar end of life as for the electric aircraft (Table 2) was assumed. First, collection, shredding, separation and sorting of the entire aircraft were assumed, after which all recyclable materials were cut off. Second, further treatment of plastic, rubber and textile materials as per Ecoinvent’s European market processes was assumed, mainly involving landfilling and incineration. Tables S21, S22 and S23 contain the unit processes for the assembly, use phase and waste treatment of the fossil fuel–based aircraft, respectively. Table S20 provides the unit process for producing the alternator.

2.9 Impact assessment

This study focuses on the top five impact categories recommended by Zackrisson (2021) for LCAs comparing batteries in electric vehicles to fossil fuel–based vehicles: global warming, mineral resources, particulate matter, acidification and ozone formation. All of these were operationalised using indicators from ReCiPe 2016 which, for the last three, specifically considers fine particulate matter formation, terrestrial acidification and ozone formation relating to impacts on both human health and terrestrial ecosystems (Huijbregts et al. 2016). For the mineral resources, we applied not only the mineral resource scarcity indicator in ReCiPe, which is the surplus ore potential (SOP) indicator (Vieira et al. 2017). Given that resource depletion can encompass different perspectives (Sonderegger et al. 2020), we also applied the crustal scarcity indicator (CSI), which has an explicit long-term (> 100 years) perspective (Arvidsson et al. 2020). Furthermore, results for all other midpoint impact categories included in ReCiPe 2016 are also provided in the SI. We used the implementation of these impact categories made available through the openLCA package of impact assessment methods (version 2.1.2).

3 Results and discussion

This section begins with hotspot analyses for the impact categories in focus, followed by a comparison of the electric aircraft with the fossil fuel–based alternative. It concludes with a discussion of the possibilities for improving the environmental and resource performance of the electric aircraft, plus recommendations for future studies.

3.1 Global warming

Figure 2 shows that, given a short lifetime, the airframe dominates global warming impacts at 63% for the EU mix and 74% for the "green" electricity. Since the airframe constitutes 49% of the aircraft mass, it being responsible for a high share of impacts is not surprising. Moreover, the carbon fibres in the composite (constituting 93% of the airframe) are highly energy intensive to manufacture (Hermansson et al. 2019). In the scenario of a long lifetime and the EU mix, the impacts of the use phase increase to the point where it becomes the largest contributor, at 43%. The reason for this is that the longer lifetime effectively means an extended use phase and that the electricity charged during this extended use phase is the comparatively carbon-intensive EU mix. By contrast, in the scenario with a long lifetime but "green" electricity, the contribution of the use phase is negligible. Rather, the airframe and the battery pack contribute considerably at similar levels (39 and 52%, respectively). The reason for the increased contribution of the battery pack in this scenario is that while the longer lifetime dilutes the impact of the airframe over more flight hours, the impact of the battery pack increases with time since it is replaced every 700 h. Just like carbon fibres, LIBs are energy-intensive products with high global warming impacts. This is particularly the case in countries with largely fossil-based electricity mixes, such as South Korea assumed in this study (Chordia et al. 2021). Also, like the airframe, the battery pack constitutes a high share of the aircraft's mass (33%). Carbon dioxide emissions from fossil energy production is the main

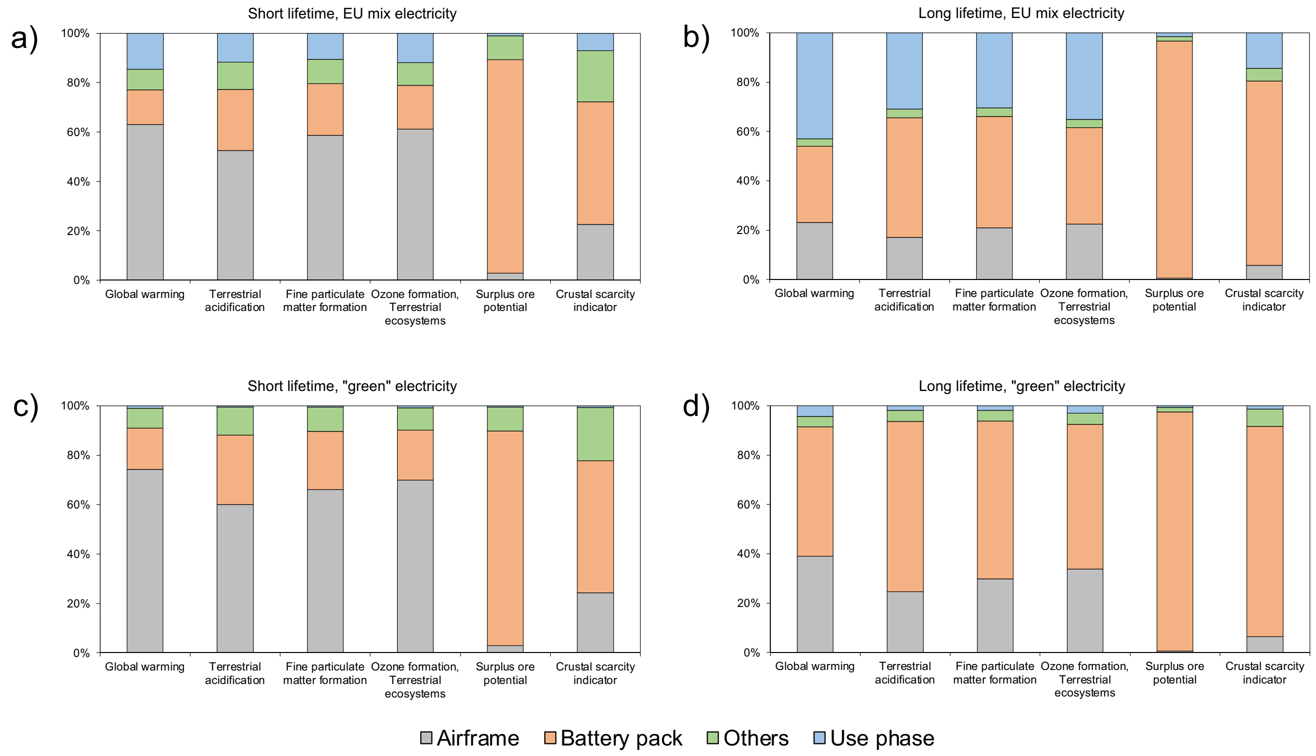


Fig. 2 Relative contribution results for the two-seater all-electric aircraft given four scenarios: **a** short lifetime (500 h) and EU-mix electricity during assembly and use, **b** long lifetime (4000 h) and EU-mix electricity during assembly and use, **c** short lifetime (500 h) and "green" electricity during assembly and use and **d** long lifetime (4000 h) and "green" electricity during assembly and use

contributing elementary flow to global warming in all scenarios, although the energy has different main uses (airframe production, battery pack production and/or aircraft charging).

3.2 Mineral resources

Figure 2 shows that the SOP indicator is dominated by the battery pack, regardless of scenario (86–97%). The elementary flows contributing the most are various metals extracted during nickel and cobalt production, including nickel and cobalt themselves. Other elementary flows contributing notably include aluminium and gallium extracted during aluminium production, plus lithium extracted during lithium brine inspissation. All these elementary flows can be linked to constituents of the battery pack, such as the NMC811 cathode and the pack material. Again, the reason for the increased contribution of the battery pack in long-lifetime scenarios is that, over a longer lifetime, the contributions of all other aircraft components are diluted. This does not apply to battery packs as they are being replaced regularly.

For the CSI, the battery pack contribution also dominates, at 50–85%. Even so, the shares are lower compared to the SOP indicator. This is because the CSI covers more elementary flows, such as the carbon extracted for energy production by fossil fuel combustion (Arvidsson et al. 2020). Here too, the elementary flows contributing the most are metals extracted during cobalt production, such as copper, nickel and cobalt. However, many other flows make notable contributions, such as coal extracted for energy production. Once again, the battery pack's contribution is greater in long-lifetime scenarios, as the pack is replaced regularly. This means its impacts are not diluted like those of other aircraft components. Only in the short-lifetime scenarios do contributions from "others" add up to more than 20% of the total CSI results (Fig. 2). These are shared roughly equally between the inverter, instrument panel, motor and high-voltage cables. These are all components which make notable contributions to the weight of the aircraft (Table 1) and which contain geochemically rare metals. The elementary flows relating to these components which contribute the most are metals extracted during copper and gold mining (mainly tellurium in addition to copper and gold), plus rare earth elements extracted from bastnäsite ore in the supply chain of the permanent magnets for the motor (mainly lanthanum and cerium, co-products of the required neodymium and dysprosium).

3.3 Particulate matter, acidification and ozone formation

As shown in Fig. 2, these three emission-related impact categories follow a pattern similar to that of the global warming impact category. For the short-lifetime scenarios, the airframe dominates (52–70%) since it is only diluted over a short period. The main contributing elementary flows are emissions from the production of energy required in the energy-intensive manufacturing of the carbon fibres. With its long lifetime, the contribution of the airframe decreases since it is diluted over a longer period. Instead, the contribution of the battery back increases, again since it is replaced every 700 h throughout the aircraft's lifetime. In the scenarios with "green" electricity, the contribution from the battery pack dominates, at 59–69%. The main contributing elementary flows here are emissions from the production of energy required for battery production. In the long-lifetime scenario with the EU electricity mix, the use phase also becomes an important contributor because, in this scenario, it is extended and the aircraft is charged using emission-intensive electricity.

3.4 General hotspot analysis

As noted in Sects. 3.1–3.3, the airframe, battery packs and use phase jointly account for most of the impacts in all scenarios for the five impact categories in focus. Results for additional impact categories can be found in Tables S24-S27 in the SI, with colour coding showing the main contributors to each impact category. Also, for these categories, the airframe, battery packs and use phase dominate the impacts, albeit in varying proportions. This is due to (i) the high shares of the aircraft's mass represented by the airframe and battery, (ii) the fact that both carbon fibre and LIBs are energy-intensive products and (iii) the relatively high share of fossil-based electricity in the EU mix. The airframe dominates the short-lifetime scenarios for global warming, acidification, particle formation and ozone formation, whereas the battery packs dominate for the SOP and CSI resource indicators. In the long-lifetime scenarios, the battery packs dominate not only mineral resource impacts but are the main contributors to most impact categories. This is because they need to be replaced five times in these scenarios, leading to the use of six sets of double LIB packs in total, while the rest of the aircraft is kept in operation. Thus, the longer the lifetime of the aircraft, the more important it is to install a battery technology with a long lifetime. The use phase contributes the most in the EU mix and long-lifetime scenario, since the aircraft then spends more time flying and a much larger share of its life cycle involves charging with emission-intensive electricity. Unsurprisingly, but nevertheless important, this shows that the longer the plane is in operation, the more important it is to source electricity with low environmental impacts.

3.5 Comparison to the fossil fuel–based aircraft

Figure 3 shows an absolute comparison between global warming impacts and CSI results for the electric aircraft and the fossil fuel based one. The focus here is on a single, emission-related impact category (global warming) and one mineral resource–related impact category (CSI, due to its long-term perspective), considering the high degree of agreement between the respective emission-related and mineral resource–related impact categories. Considering global warming first, the electric aircraft comes out worse than the fossil fuel-based one given the short lifetime of the electric aircraft. This is due mainly to the high contribution from the airframe. This emphasises the importance of keeping the electric aircraft operational for as long as possible, in other words, ensuring a long lifetime. For the long-lifetime scenarios, the global warming impact of the electric aircraft becomes lower than that of the fossil fuel based one. This is further emphasised in the most beneficial scenario for the electric aircraft that of both long lifetime and "green" electricity. Given this scenario, the global warming impact of the electric aircraft is less than half of that of the fossil fuel based one. For the fossil fuel–based aircraft, the use phase dominates global warming due to carbon dioxide emissions from combusting aviation fuel.

Considering then the CSI results, the downside of the electric aircraft becomes clear—the battery's rare metal content gives the electric aircraft a notably higher CSI than the fossil fuel based one in all scenarios. This higher mineral resource impact of the electric aircraft is even clearer for the other mineral resource indicator that has been applied—the SOP—for which results can be found in the SI. As for global warming,

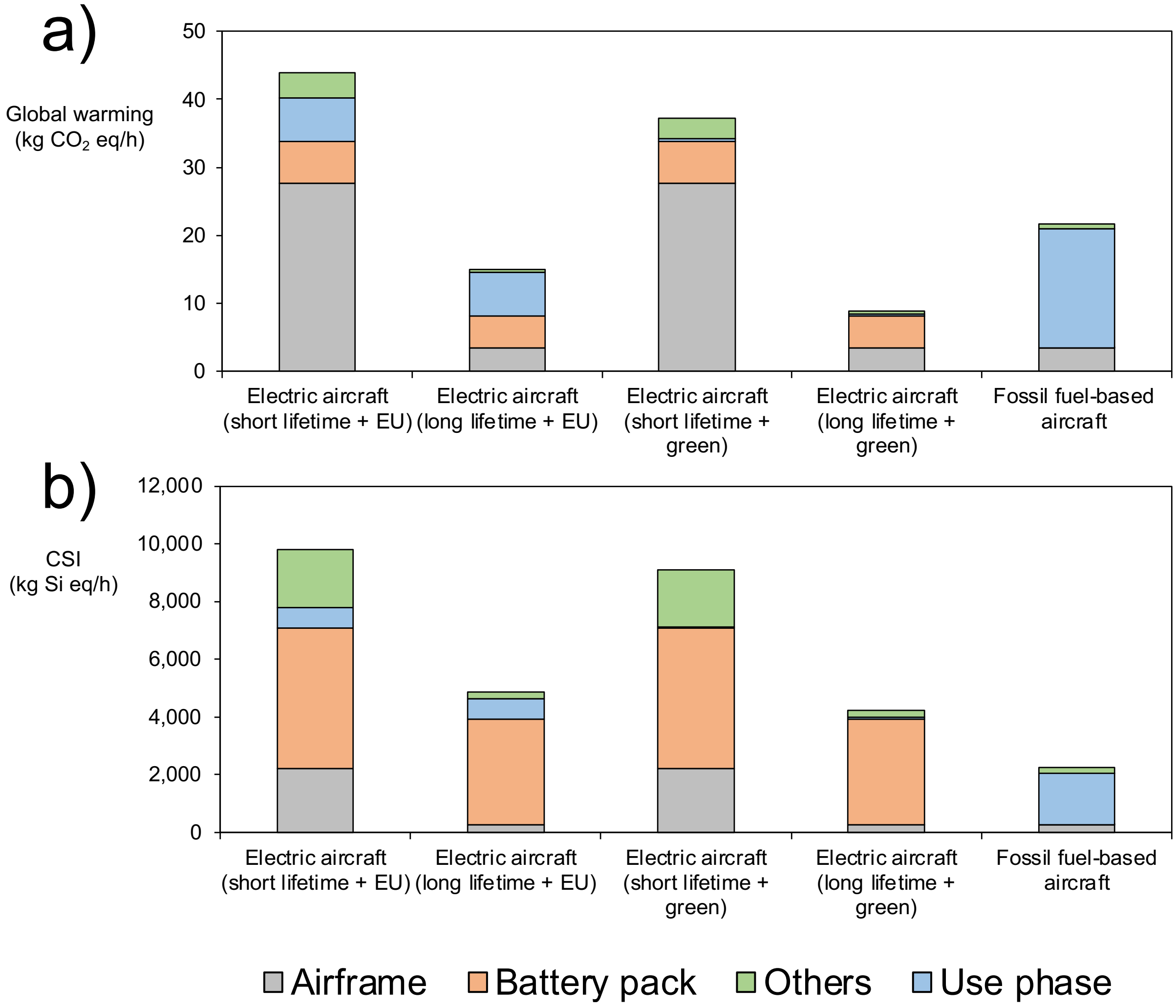


Fig. 3 Absolute comparison of **a** global warming impacts and **b** the crustal scarcity indicator (CSI) results for the electric aircraft and the fossil fuel based one. The short lifetime is 500 h, and the long lifetime is 4000 h. "EU" and "green" refer to the electricity that is sourced for the aircraft assembly and use phases. The lifetime of the fossil fuel–based aircraft is 4000 h

the CSI of the fossil fuel–based aircraft is dominated by its use phase, due to the carbon extracted for the fuel.

Detailed results for the fossil fuel–based aircraft with all impact categories assessed can be found in Table S28. There is also a comparison between the fossil fuel–based aircraft and electric aircraft scenarios in Table S29.

3.6 Potential improvements and further studies

As shown in Sect. 3.4, the airframe, battery packs and use phase are the three hotspots for the electric aircraft. The reason for the high impacts of its airframe is mainly the carbon fibre–reinforced composites. Two different approaches, which can also be combined, have been shown to reduce the environmental impacts of carbon fibre–reinforced composites: (i) using recycled carbon fibre–reinforced composites and (ii) using bio-based carbon fibres from lignin (Hermansson et al. 2019). However, both the recycling of carbon fibre–reinforced composites and the production of lignin are multifunctional processes. In the first case, impacts must be allocated between the first and second product, and in the second, impacts must be allocated between different wood products (lignin, cellulose and so on). Thus, the choice of allocation approach influences the environmental impacts (Hermansson et al. 2020, 2022), something which should be considered in future studies.

Regarding the battery's impacts, Chordia et al. (2021) showed that switching from the South Korean fossil-based energy system to one based mainly on non-fossil-based energy (such as that of Sweden) can reduce the global warming impact of the LIB cells by approximately 50%. Acidification would also be notably reduced, although not by as much. Thus, a recommendation for reducing global warming, acidification and other emission-related impacts is to purchase batteries produced in countries with energy mixes based mainly on non-fossil sources or from producers with dedicated sourcing of non-fossil energy for their facilities, for example, through green tariffs or in-house renewable energy production. However, mineral resource impacts are unlikely to be as reduced by such efforts, since these originate mainly from the use of nickel, cobalt, copper and lithium in NMC battery cells (Chordia et al. 2021).

Reducing mineral resource impacts would probably require a shift to other types of battery cells. Possibilities to investigate in future studies include lithium-iron-phosphate (LFP) batteries and next-generation batteries such as lithium-sulphur types, which contain lithium but few other rare materials. Lithium-sulphur batteries have particularly high anticipated specific energy densities (2500 Wh/kg in theory and 800 Wh/kg expected in practice at cell level, compared to approx. 200–250 Wh/kg for LIB cells), which might make them suitable for aircraft applications (Hess et al. 2019). Furthermore, improving the cycle life of the battery (regardless of type) would reduce the need for battery replacements during the aircraft's lifetime. Such work is already ongoing; the 2022 version of the new-generation, all-electric aircraft from Pipistrel, the Velis Electro, already achieves a battery cycle life three times longer than that of the Alpha Electro.

An improvement to the use phase has already been considered in this study, by sourcing electricity that has less impact. Analogous to the battery production, this can be done by (i) charging the aircraft with non-fossil electricity (if it is readily available in the grid mix when the plane is being used), (ii) sourcing non-fossil energy through green tariffs or (iii) in-house renewable electricity production. As shown in Fig. 2, the impacts of electricity charging during the use phase become more important the longer the lifetime of the aircraft.

Finally, future studies might consider additional approaches to uncertainty analysis. This study has applied a scenario analysis approach (Igos et al. 2019), focusing on electricity mixes and aircraft lifetime. While these parameters have been shown to be influential, there are additional uncertain parameters along the life cycle. For example, the exact design of two-seater aircraft might vary, such as the choice of seat fabric. End-of-life processes might also vary depending on the availability of local end-of-life processes where the aircraft is scrapped. There are also various uncertainties in the background system data obtained from the Ecoinvent database (Weidema et al. 2013). To account for a wider range of uncertainties (and their propagation) throughout the life cycle, Igos et al. (2019) recommend global sensitivity analysis using Monte Carlo simulations and other, more advanced approaches to uncertainty analysis. These could be relevant in future, more detailed LCA studies of electric aircraft.

4 Conclusions

The main conclusion of this study is that two-seater all-electric aircraft can achieve lower environmental impacts than two-seater fossil fuel–based types, if they can withstand operation over a sufficiently long lifetime. This is because a long lifetime enables the burden of the airframe to be distributed over a high number of flight hours, while the benefit of efficient electric propulsion saves operating emissions relative to the fossil fuel–based aircraft. Moreover, several of the environmental impacts of the all-electric aircraft can be reduced by charging with non-fossil electricity. However, there is a clear trade-off with mineral resources: the all-electric aircraft has higher mineral resource impacts than the fossil fuel-based one, mainly because of the metals in the battery pack. Two potential environmental and resource improvements to the all-electric aircraft are recommended for investigation in future studies: (i) bio-based and/or recycled carbon fibres for the airframe and (ii) battery cells with a longer cycle life to reduce the number of battery pack replacements.

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Data availability The data supporting the findings of this study was provided in Sect. 2 and in the Supporting Information (SI). Access to some upstream data requires access to the Ecoinvent database.

Declarations

Conflict of interest The authors declare no competing interests.

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